



Owens Valley Millimeter Array



CO, mm, and NIR Observations of High-Redshift Submillimeter Galaxies

OVRO group (High-z CO):

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SCUBA group (Lens Cluster Survey):

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Keck-CIT group (NIRC/NIRSPEC):

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CO Observations

- **CO(3-2) detected in SMM J02399-0136 ($z = 2.8$) and SMM J14011+0252 ($z = 2.6$)**
 - $L'(\text{CO}) \simeq 2 \times 10^{10} h_{65}^{-2} \text{ K km/s pc}^2$ ($q_o = 0.5$)
 - $M(\text{H}_2) \simeq 4 \times 10^{10} h_{65}^{-2} M_{\odot}$ ($\alpha = 2$)
 - * $\alpha(\text{MW}) = 4.8$ for CO(1-0) in Galaxy
 - * $\alpha(\text{ULIGs}) \simeq 1/4 - 1/2 \alpha(\text{MW})$
 - * $\text{CO}(3-2)/\text{CO}(1-0) \simeq 0.5 - 1$
 $\Rightarrow \alpha \simeq 2$
 - $\Delta V \sim 200 - 700 \text{ km/s}$
 - $D(\text{CO}) \sim 15 \text{ kpc}$ for SMM J14011+0252!
 - $M_{\text{dyn}} \lesssim 10^{11} M_{\odot} \sim M_{\text{gas}}$
 - $L(\text{FIR})/L'(\text{CO})$ and $L(\text{FIR})/L(\text{radio})$ ratios similar to low- z ULIGs
- **SMM J02399-0134 ($z = 1$) detected in CO(2-1) (PdB & OVRO)**
 - $S(\text{CO}) \sim 1 - 2 \text{ Jy km/s}$ while expecting about 6 Jy km/s
 - $L'(\text{CO}) \simeq 10^{10} h_{65}^{-2} \text{ K km/s pc}^2$
 - Sub-mm luminosity dominated by AGN activity?
- **CO detection rate is 100% (so far) !!**

NIR Observations

- Keck/NIRC NIR Imaging Survey
 - Detected new $K=22.5$ galaxy corresponding to SMM J00266+1708
 - * Optically invisible ($I > 26$ with HST)
 - * OVRO 1.3mm continuum detection gives accurate position
 - * Most likely at high- z , $z = 3.5 \pm 1.5$
 - $\sim 40\text{--}70\%$ of sub-mm sources are faint/red galaxies which are undetected in the optical/ultraviolet ($I > 26\text{--}27$)
- Keck/NIRSPEC Spectroscopy
 - Tentative line for ERO-N4 ($H\alpha$ at $z \simeq 2.2$)??
 - Failed to detect lines in ERO-H5 and J5
 - Most faint-red ULIG/sub-mm (unlensed) expected to have $K \sim 21 - 26 \rightarrow$ NGST!?!

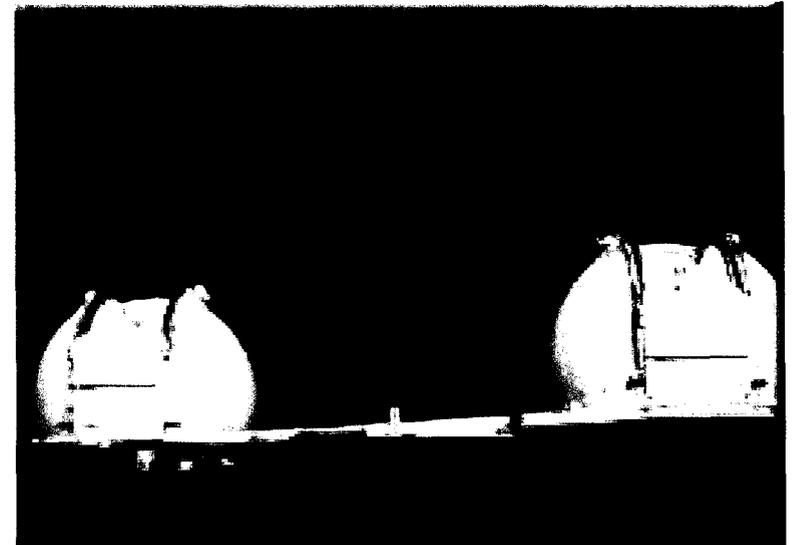
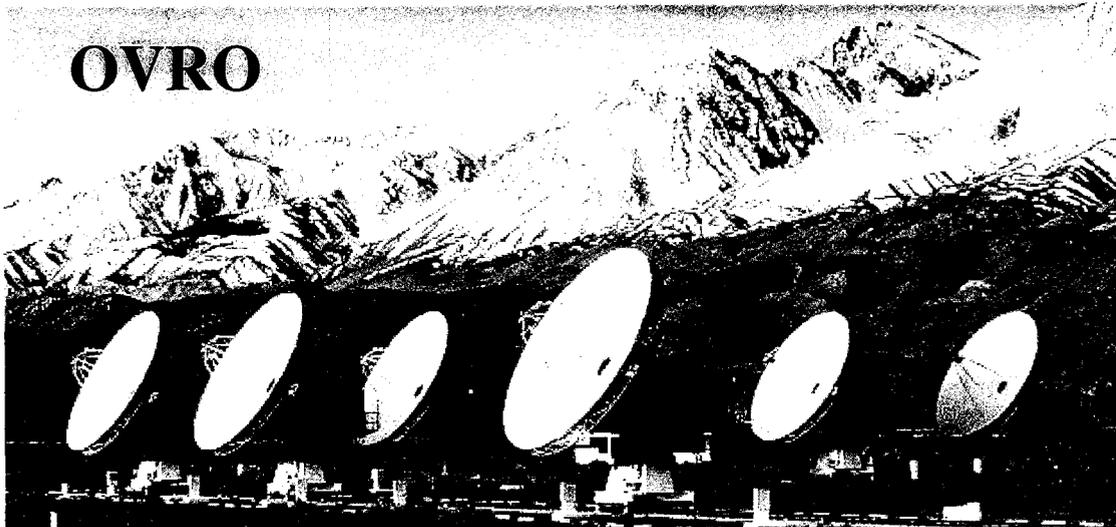
Concluding Remarks

- Sub-mm galaxies are gas-rich, high-z ULIGs (\neq Lyman-break sources)
- Account for a significant fraction of both the star-formation and AGN activity at high-z
- Could represent the formative phases of ellipticals/spheroidals:
 - High number density ($10^3 - 10^4 \text{ Mpc}^{-3}$)
 - Associated with mergers
 - Massive molecular gas reservoirs ($\gtrsim L^*$ galaxy)
- For Cluster Lens Survey, 8/9 (90%) at $z \gtrsim 2$
- Approximately 60% are undetected at optical wavelengths (5/9–6/9)
- Approximately 40–70% are very red (4/9–6/9)
 - Future mm/submm/FIR/IR/NIR observations crucial
 - Redshifts from CO lines!
(skip the UV/optical/NIR!)
 \Rightarrow ALMA, CARMA, LMT, GBT
 - * Wide Bandwidth
 - * Frequency Coverage
 - * Sensitivity

CO and NIR Observations of High-z Submillimeter Galaxies

Galaxies

David T. Frayer



Theoretical Motivation

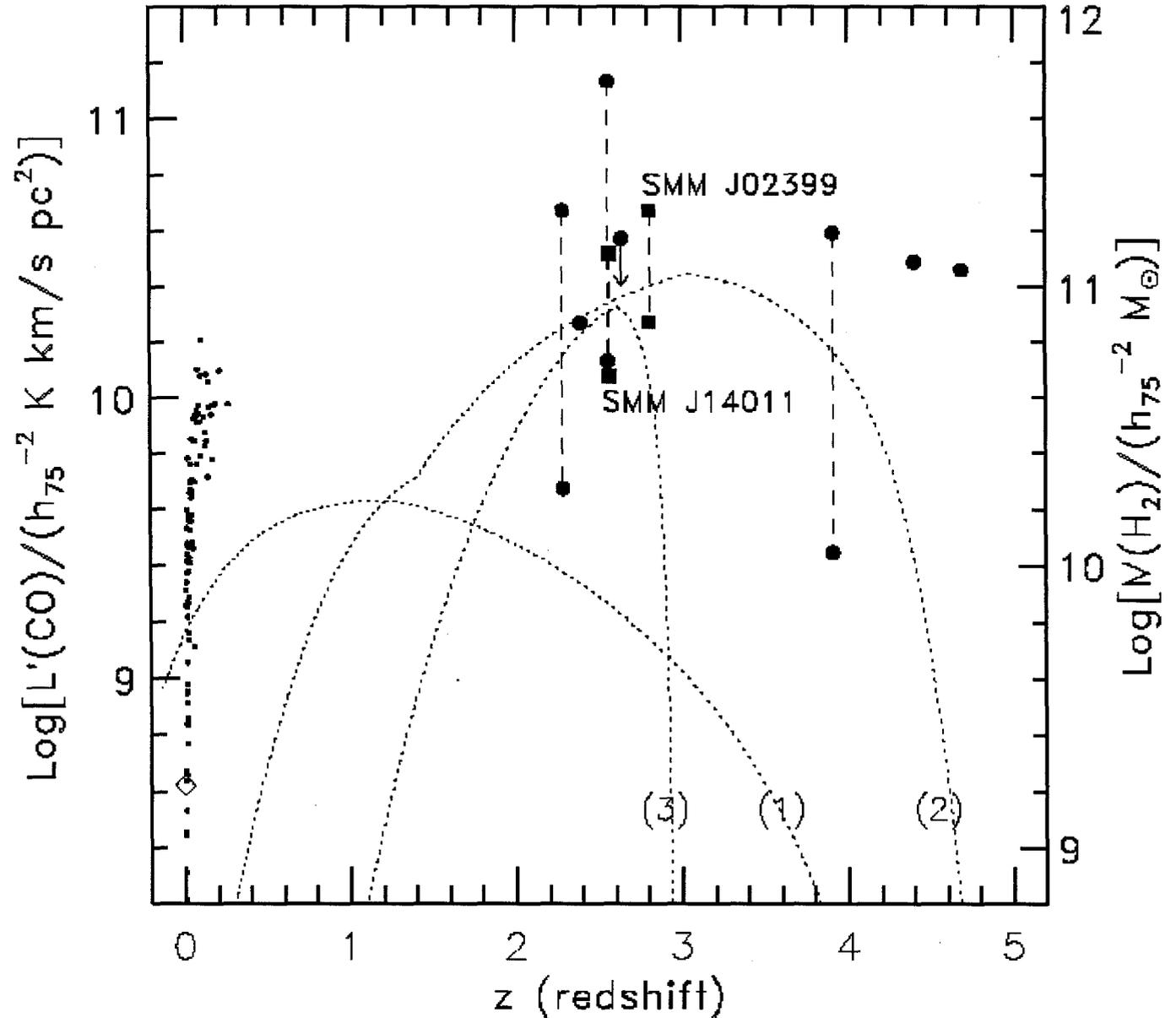
More CO and dust in the past for massive galaxies!!

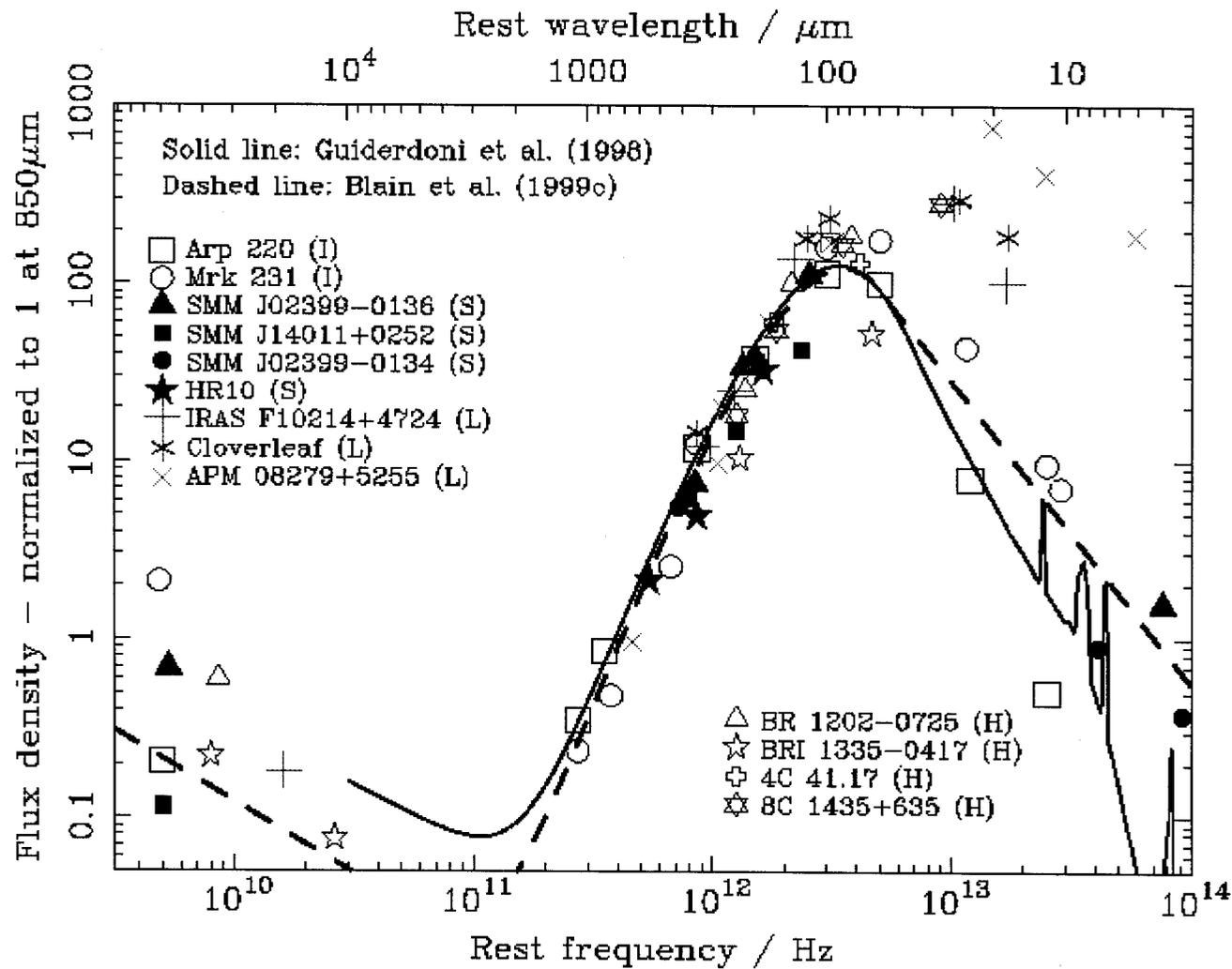
(1) Spiral Disk model

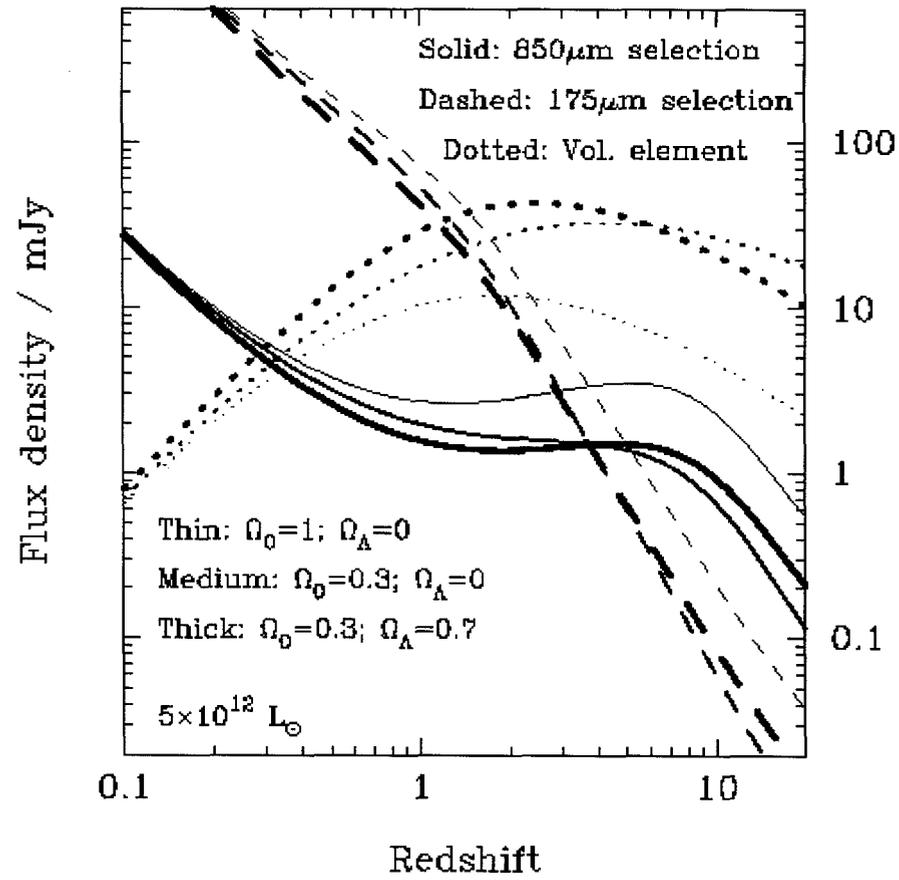
(2) Elliptical Model

(3) Major Merger Model

Models based on Frayer & Brown 1997

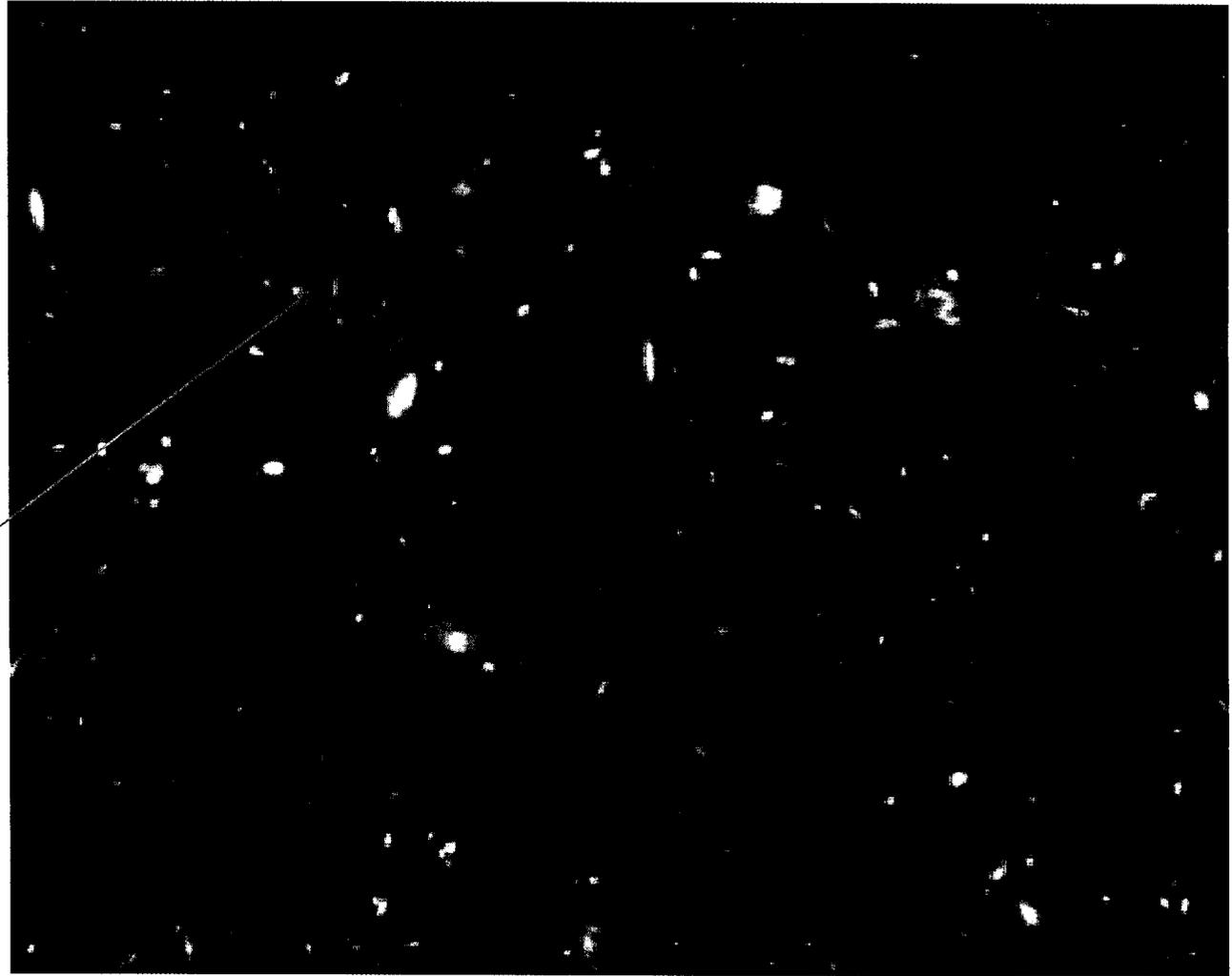


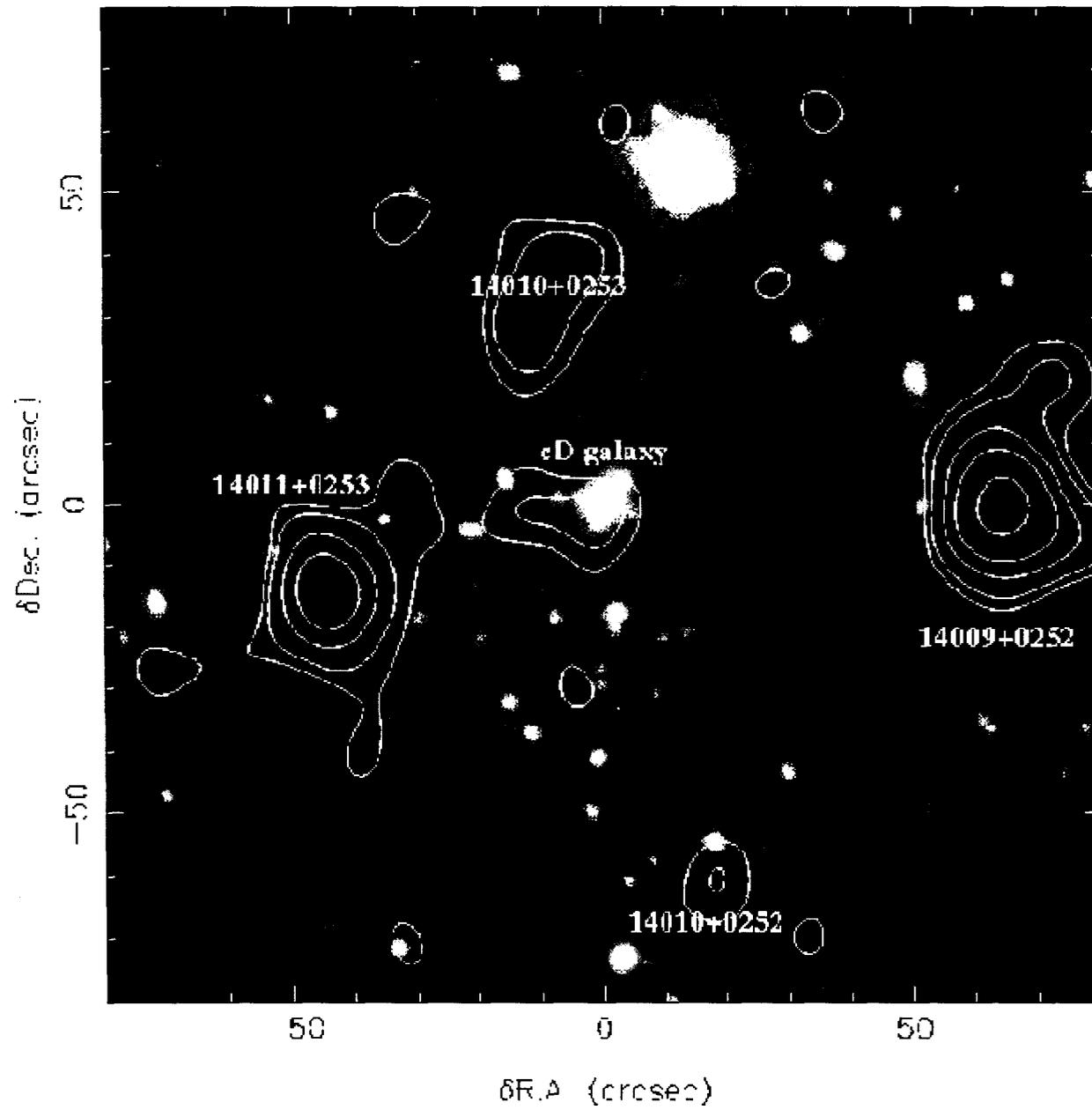




Brightest
Submm
galaxy may
not even be
detected in
the HDF!

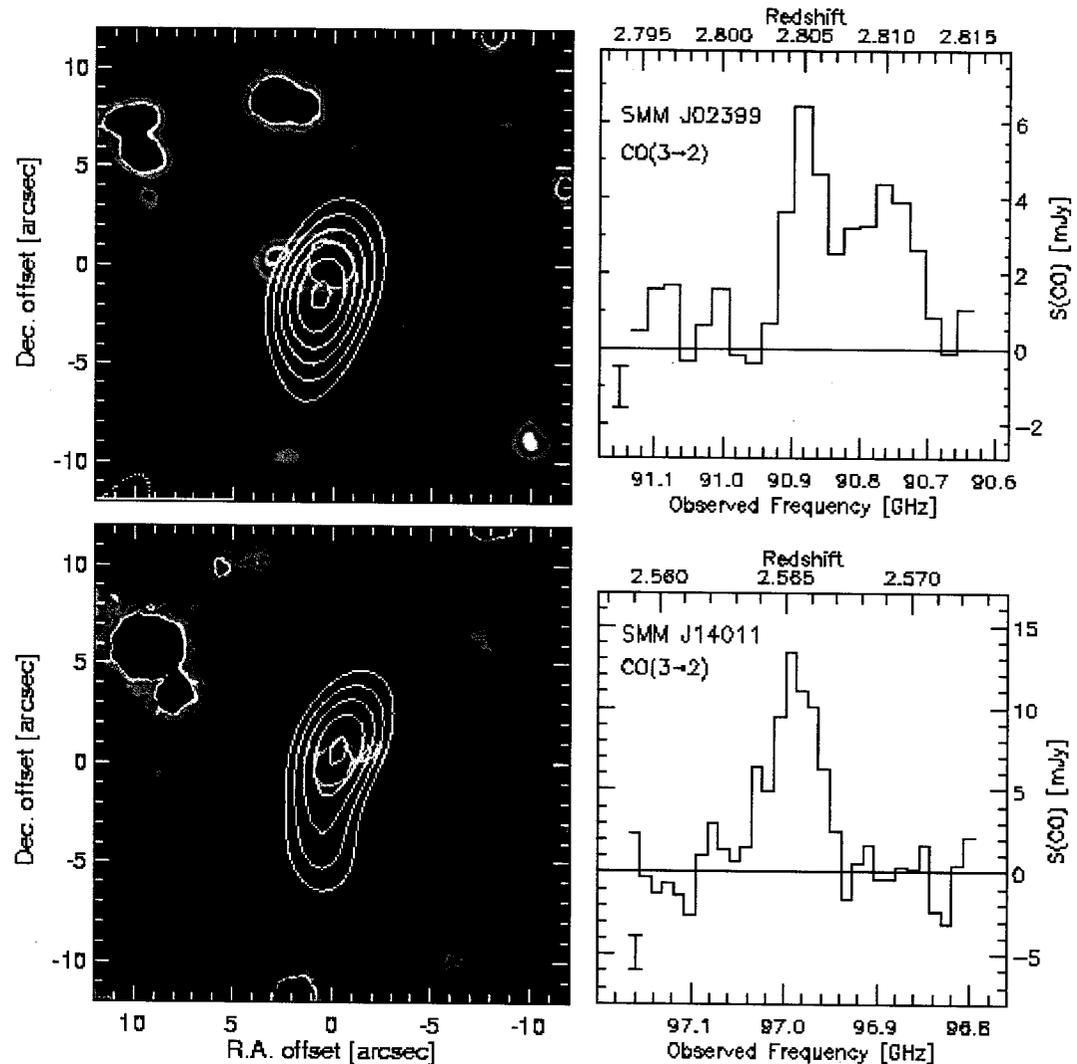
(Downes et al.
2000)





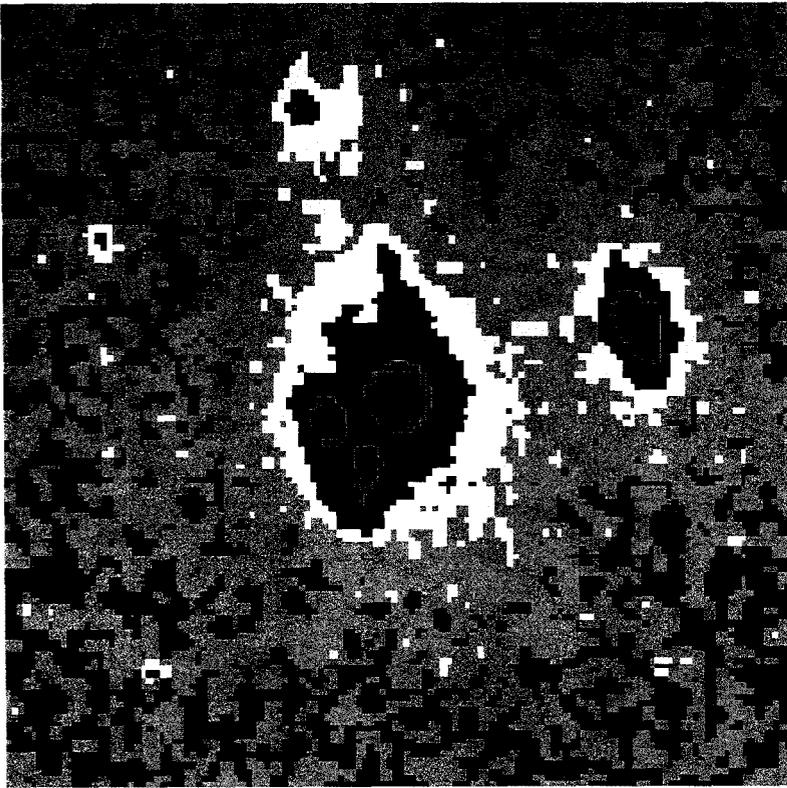
CO Detections at OVRO

- $M(\text{H}_2) \sim 10^{11} M(\text{sun})$, depending on conversion factor and excitation.
- Enough gas to fuel the star formation implied by the submm data, $L(\text{FIR}) \sim 10^{13} L(\text{sun})$
- Similar CO/FIR properties as local ULIGs



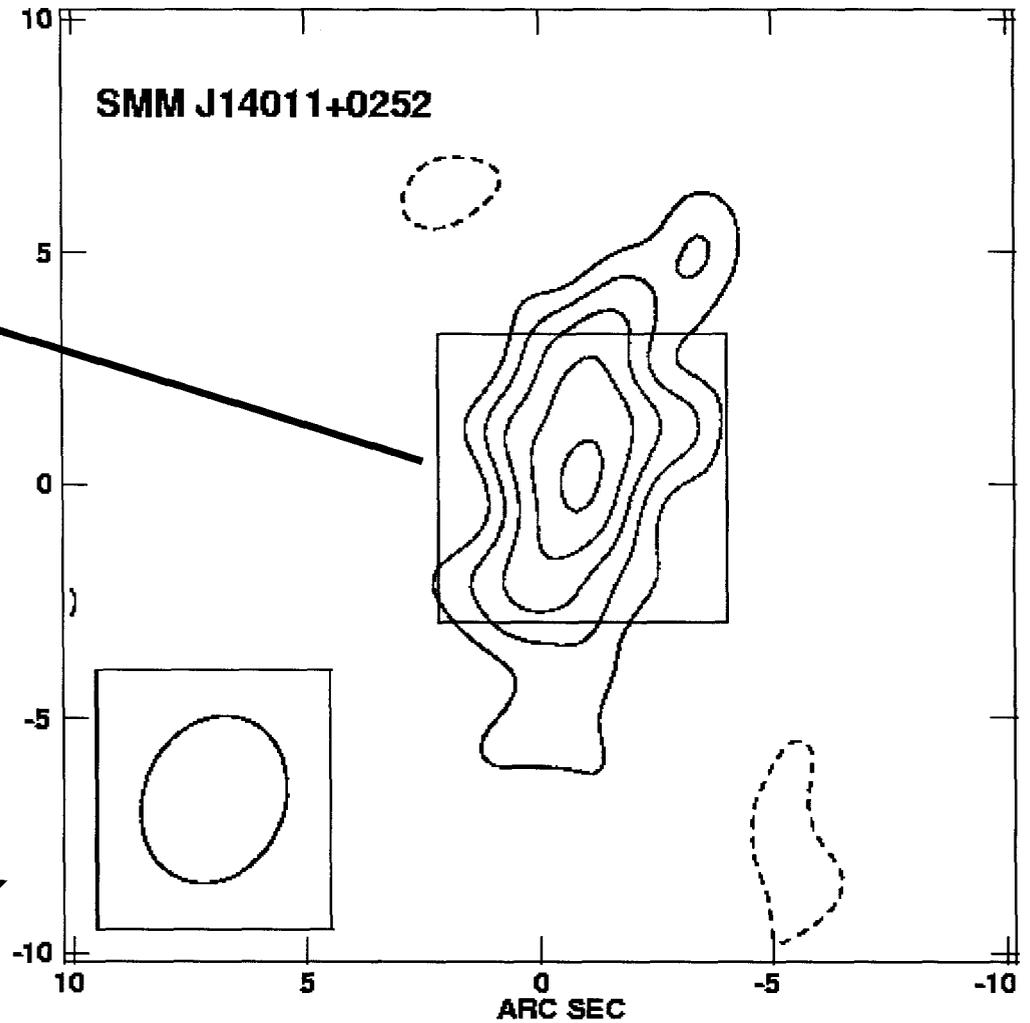
Frayser et al. 1998, 1999

SMM J14011+0252

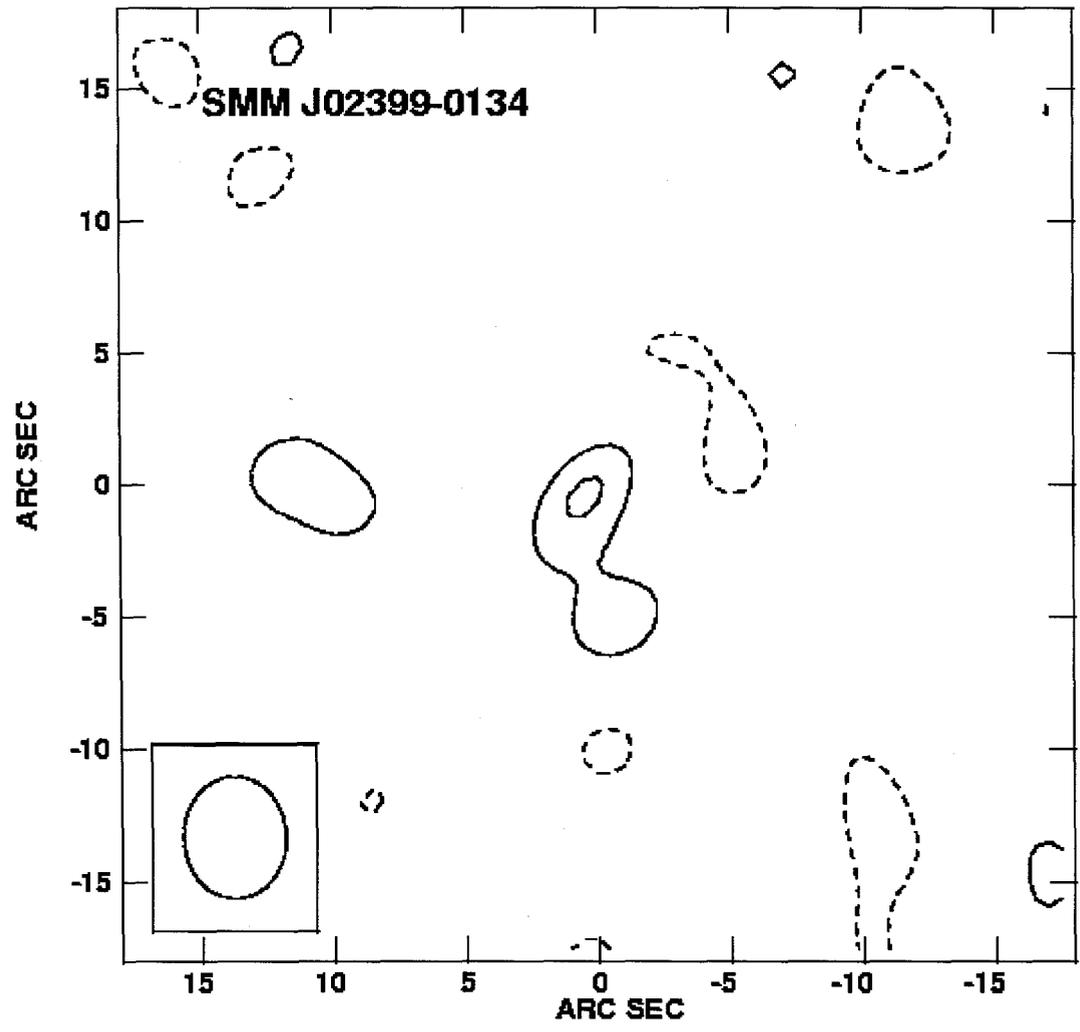


HST R-band (Small)

CO High-Resolution



Levs = 0.75mJy * [-3, -2, 2, 3, 4, 5, 6]

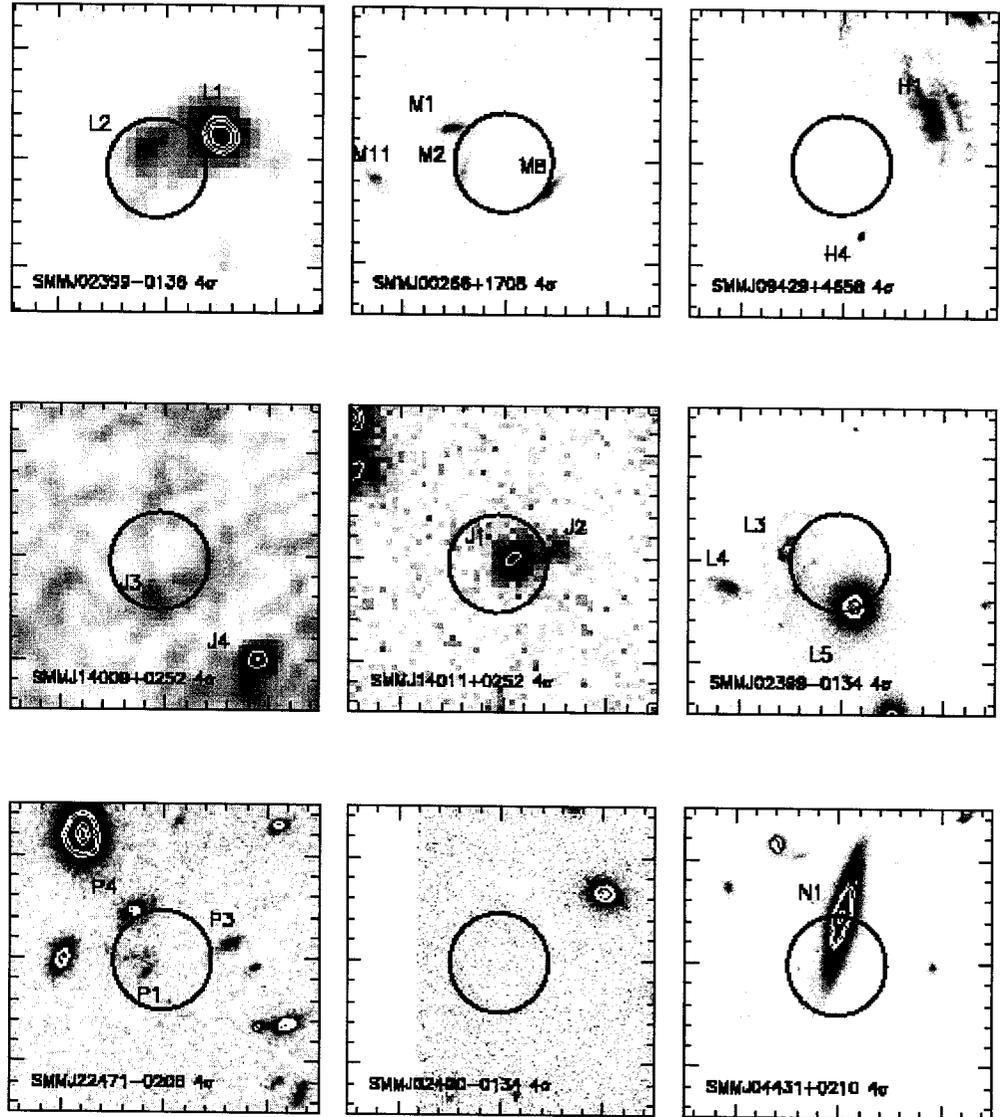


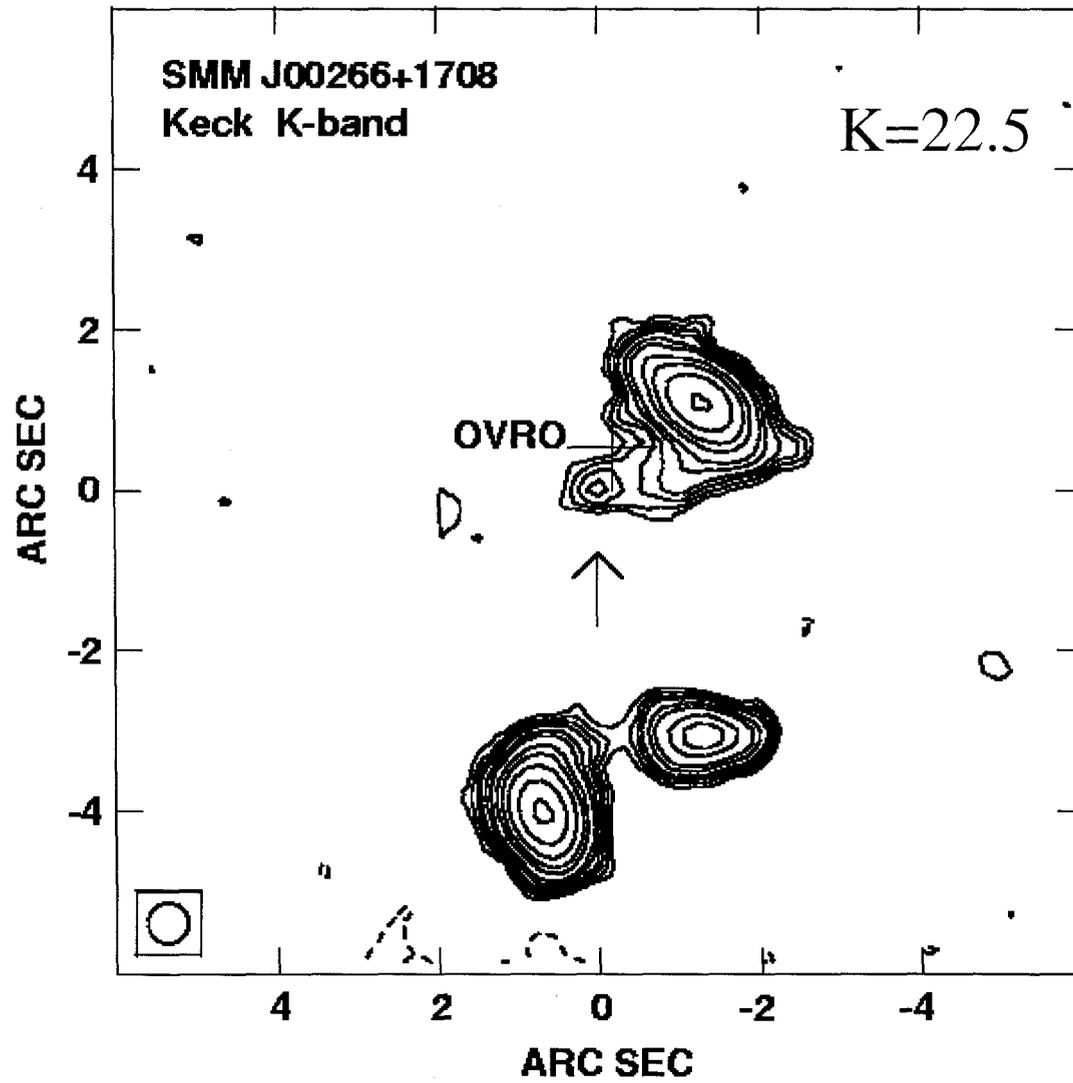
Levs = 1.0 mJy * [-2, 2, 3]

SCUBA Cluster Lens Survey

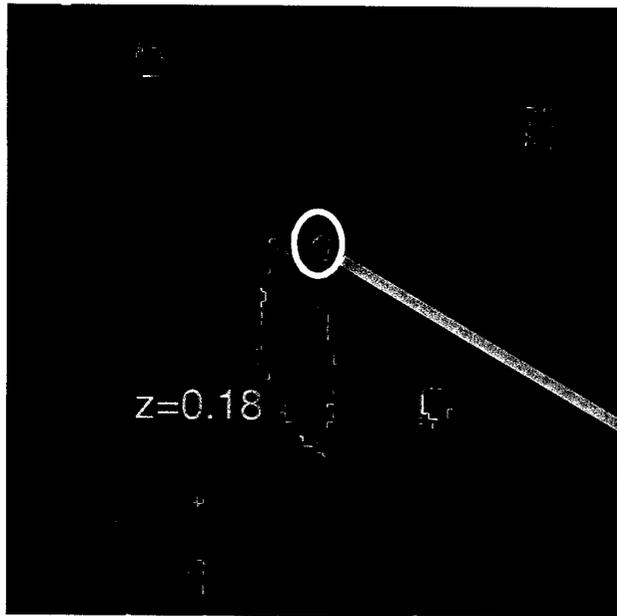
Deep I-band Images (I~26 mag) of brightest submm sources in Smail et al. survey:

- 3/9 detected in CO
- 4/9 detected in I-band
- 5/9 detected only in K-band
- 6/9 detected in radio
- 4/9 with optical redshifts



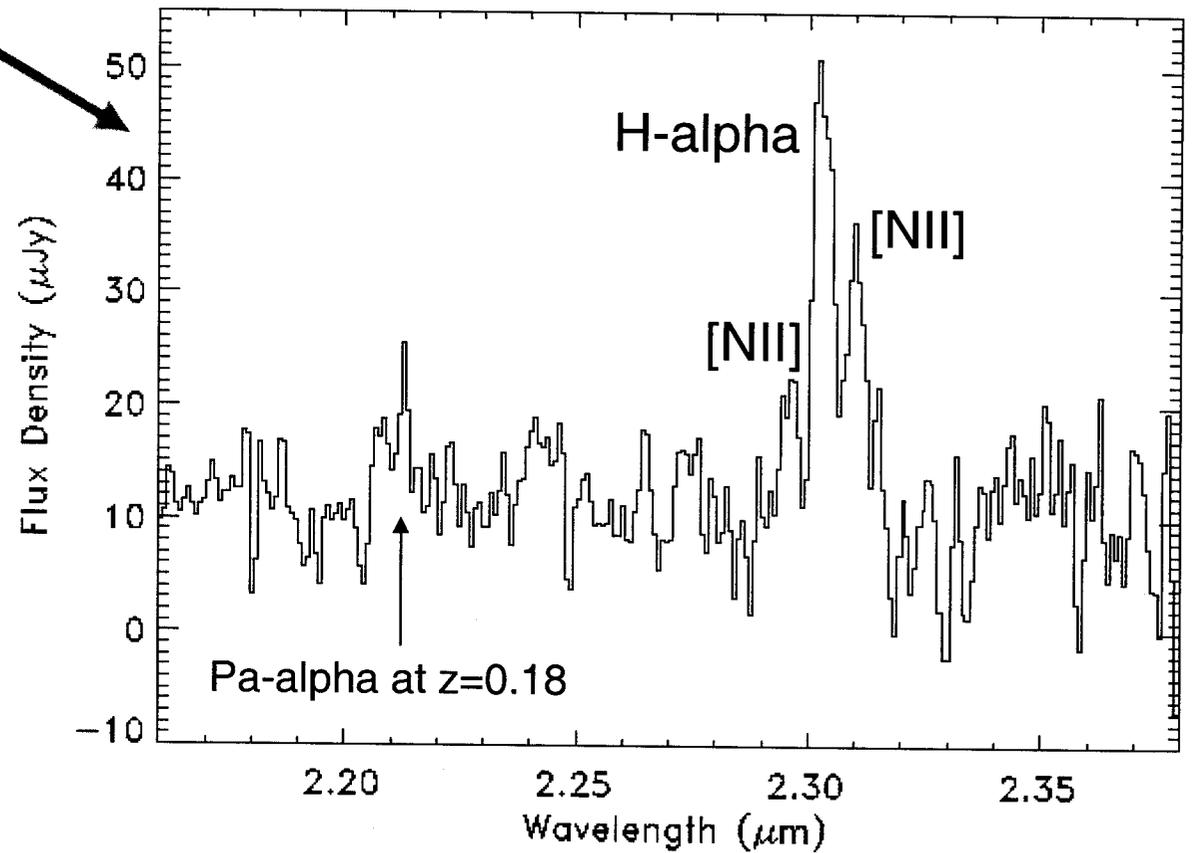


Frayser et al. 2000



ERO-N4

$z=2.51$



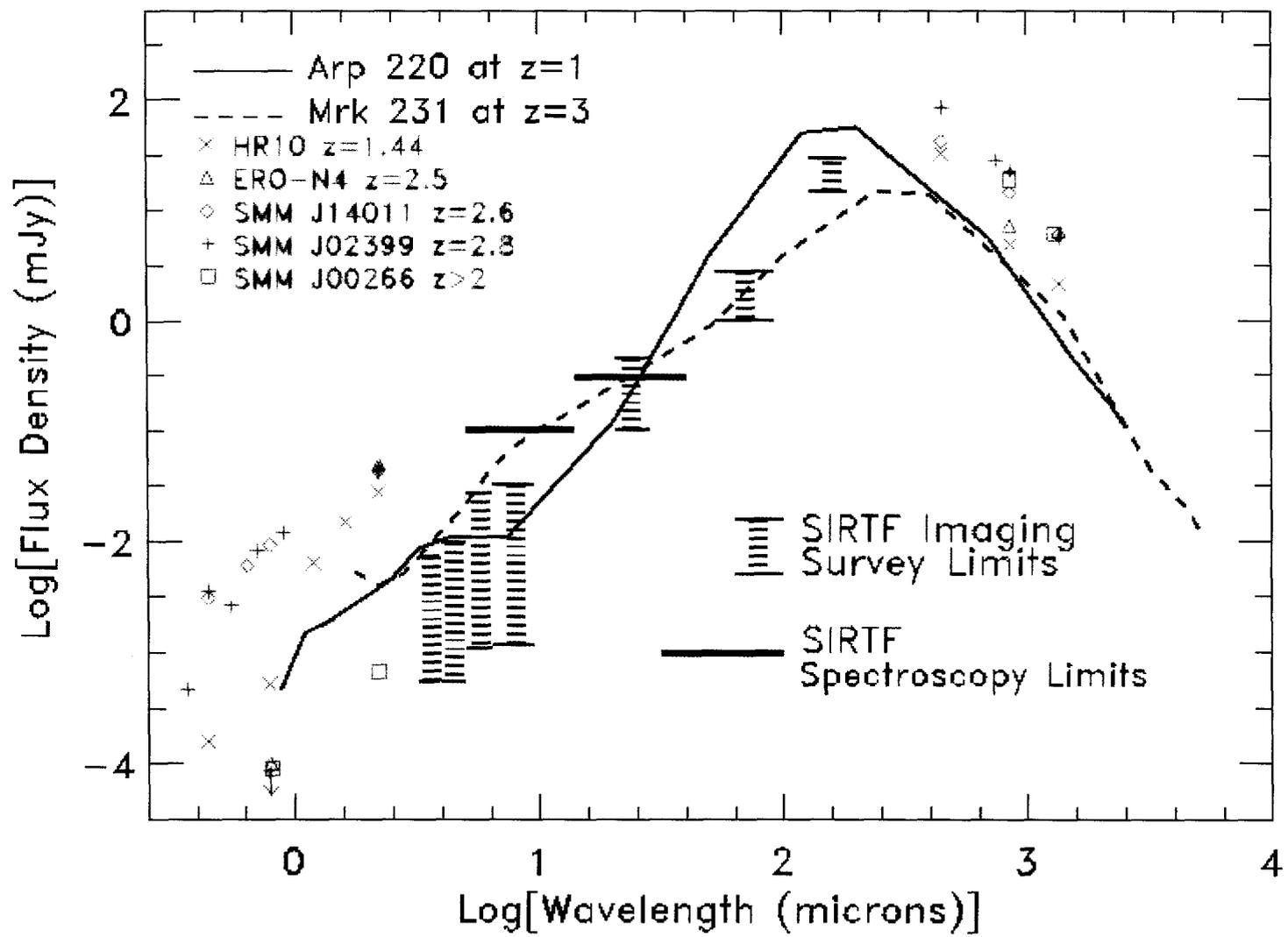
$K=19.3$

- First redshift for a submm galaxy that is an ERO.
- Most distant ERO known to date.

Brightest $850\mu\text{m}$ Sources in SCUBA Cluster Lens Survey

Galaxy[8]	$S(850\mu\text{m})$ (mJy)	Redshift	K -mag	Identification Data
SMM J02399-0136	25.4	2.808 [2]	19.1 [6]	CO[2]
SMM J00266+1708	18.6	> 2.0 [10]	22.5 [3]	1mm [3]
SMM J09429+4658	17.2	> 3.9 [10]	19.6 [9]	I-K>6 [9]
SMM J14009+0252	14.5	> 0.7 [10]	21.2 [5]	radio [5]
SMM J14011+0252	12.3	2.565 [1]	18.0 [5]	CO [1]
SMM J02399-0134	11.0	1.062 [11]	16.3 [11]	CO [7]
SMM J22471-0206	9.2	> 1.8 [10]	20 [4]	J-K>2.5 [4]
SMM J02400-0134	7.6	> 2.4 [10]	22 [4]	J-K>2.5 [4]
SMM J04431+0210	7.2	2.5 [4]	19.3 [9]	I-K>6 [9]

[4]=Frayer et al. 2001, in prep



Conclusions:

- Most (all) submm galaxies are gas-rich and are undergoing at least some star formation
- Still can argue about AGN vs Starburst
- About 50% of population is too faint/red to be detected in the optical/UV
- Future NIR-mm observations are the key for understanding these systems (i.e., **SIRTF, ALMA,.....!!!**)